MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

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CONTENTS

PART I

INTRODUCTION

The Alps the European type of the Asiatic mountain arc.— Studies of mountain structure have made use chiefly of profiles, or cross-sections, at right angles to the crests of the ranges. In recent years and to a relatively small extent only, longitudinal sections have also been figured in order to take account of the directions of pitching folds. In the geological map the plan of the region is of course represented, but chiefly with a view to fixing the areal distribution of the formations; and so far as known the discussion of the mechanics of the folding process has been restricted to the two dimensions included in the normal profile. While the reason for this may be in part the difficulty of representing more than two dimensions of space, it is no doubt due largely to a general belief that all significant elements in the problem can be properly set forth in the transverse section.

It was Eduard Suess who first clearly demonstrated the deep significance of the plan of arrangement of Asiatic or Euro-Asiatic mountain arcs. The Alps are to be regarded, as Suess has clearly shown, as an extension into Europe of the Asiatic mountain system, which includes also most of the ranges of southern and southeastern Europe. The name "Asiatic arcuate structure" or "Asiatic structure" is well chosen for the reason that this entire political division of Asia with the single exception of the peninsula of Hindustan, but including the entire group of island fringes as far out as the Bonin Islands and the Mariannes, is characterized throughout by the most pronounced of mountain arcs. Generally less typical, the same structure is represented upon the western continent by the sweeping arcs of Alaska, certain northern ranges of the Rocky Mountain system, and the Appalachians and West Indian ranges; while the only marked example upon the African continent is the Atlas range in the northwest.

In view of this extent and evident importance of the mountain arc, and its typical illustration in the Alps, no structural geologist can afford to remain in ignorance of at least the broad outlines of the Alpine problem. Whatever may be true of some other mountain districts that have been studied, here at least the plan as well as the vertical sections must be fully considered in the discussion of the mechanics of the folding process.

Conditions favorable for tectonic studies of the Alps.—No mountain region has excited so much interest in its structural problems as has the Alps. This is in part to be explained by its location in the very heart of Europe easily accessible to the geologists of every European nation, and in part by the scenic and hygienic qualities of the Swiss highland which have made it the playground not only of Europe but of the world as well. Its rugged features have been mapped in much detail and with praiseworthy accuracy, and the cartography of the country is the pride of every enlightened Swiss. Switzerland has, moreover, produced structural geologists who have ranked high among their fellows, and the complex problems of Alpine tectonics have gradually evolved from the early conception of Escher von der Linth to the brilliant theory of

Bertrand, later worked out by Schardt, Suess, Lugeon, Termier, Heim, and others.

It should not be forgotten that there are in the Alps some natural conditions which are favorable to the solution of its structural problems, and without which it seems likely that we should have advanced but slowly toward the goal. The rocks of which the Alps are composed are very largely sediments, which in a considerable portion of the area are uncrystalline and so richly fossiliferous that it has generally been possible to determine the place of each local bed within the vertical column. Almost as important in view of the peculiar character of the deformation, there is a horizontal differentiation of the beds from the northwest to the southeast which is recognized both in the petrographic character and in the fossils of the several formations. Thus it has been possible upon this basis to determine in some measure the lateral as well as the vertical displacements of the beds.

To a small extent only and in relatively few of the significant localities have the beds been greatly altered through the intrusion of igneous masses; and the regional metamorphism has seldom been so great as completely to destroy the identity of formations. Sculptured by glaciers into a fretted upland, the sheer mountain walls of the Alps, bare as they are of vegetation, often reveal in wonderful perfection all the intricacies of their complex structure. Thus with all its complexity the great problems of Alpine structure appear to be soluble, and it is easy to see that if differences of opinion still exist, we are none the less slowly approaching the goal.

To all these natural advantages for study there are to be added the network of mountain railways which surpass anything of the kind to be found elsewhere, a wealth of good hostelries, even at high and not easily accessible points, the numerous refuges, and the fraternity of competent and hardy guides.

For some other regions, such for example as that of southwestern New England, no one of the above-mentioned natural conditions is realized, and there is therefore good ground for believing that the problems of structure are in consequence practically insoluble. It is the author's belief, based upon many

years of study in the region, that though in certain favored districts maps and sections revealing internal structure may be prepared, for the larger portion of the region the most that can be expected is to derive a general notion from the study of the key localities.

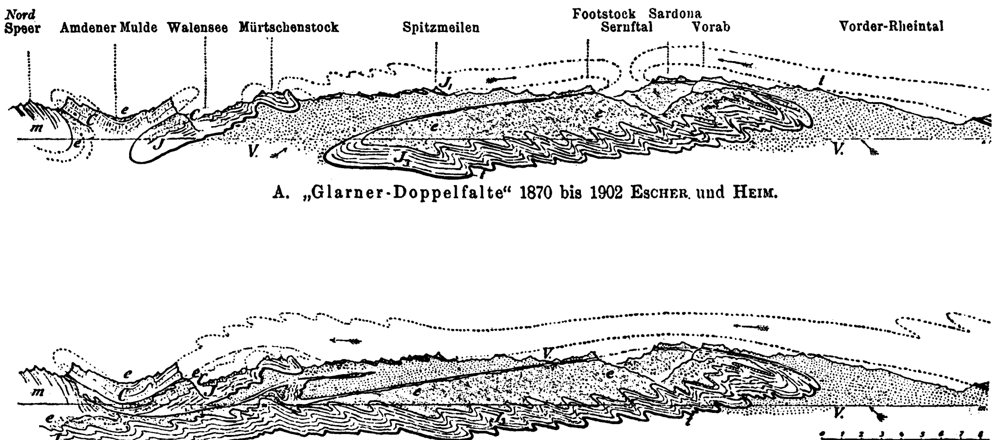
The blanketing series of slices which make up the Alps.—It is not our primary purpose to present in detail at this time the modern Swiss interpretation of Alpine structure, or the objections which have been raised against it. Such an outline, important as it is for American students, who are likely to be bewildered by the many new terms, particularly when these terms are found in the original German and French sources, must be deferred until after the mechanics of the process has been considered. It is perhaps sufficient to allude here to the fact that the conception of series of blanketing slices (*Decken* or *nappes de recouvrement*), which originated in the mind of Bertrand in 1884,[1] was worked out independently and applied by Schardt in 1890–93 in the Voralpzone, and again by Lugeon in 1896, has now overcome all opposition in Switzerland, and, following its adoption by Heim himself in 1903, it has been the accepted doctrine of all Swiss workers without exception.

The story of the gradual acceptance of this theory reads like a romance and probably has no parallel in the history of geology. When the idea was first suggested by Bertrand upon the basis of his studies of the coal basin of northern France, no one seems to have taken the theory seriously as it applied to the Alps, since its author had never studied that region upon the ground. When nine years later Schardt was independently forced to similar conclusions in order to explain the structure within the area between the lakes of Geneva and Thun, he was vigorously opposed, by Lugeon among others. Hardly three years later Lugeon had been forced by his own studies to accept the new doctrine, and he is now its most prominent champion. Heim himself, whose name for almost a generation had been identified with the earlier theory of the double fold, accepted the new theory in 1903, and thereafter

[1] Marcel Bertrand, "Rapports de structure des Alpes de Glaris et du bassin houiller du Nord," *Bull. soc. géol. de France* (3), XII (1884) 318–30, Pl. 11.

it became standard doctrine throughout Switzerland. From Alpine countries outside Switzerland there have come examples of prominent structural geologists long identified with Alpine studies who first fought and later defended the Bertrand-Schardt conception of Alpine structure.

If a personal incident may be permitted, the writer's own experience has not been greatly different. In the summer of 1912 he entered the central Alps with the paper of Willis[1] in hand,



A. „Glarner-Doppelfalte" 1870 bis 1902 ESCHER und HEIM.

B. „Glarner-Deckfalten" 1883 BERTRAND, 1892 SUESS, 1903 HEIM.

m = Molasse (Nagelfluh, mitteltertiär)
e = Flysch (alttertiär)
C = Kreide
J = Jura
t = helvetische Trias (Röthidolomit)
V = Verrucano (Sernifit).

FIG. 1.—The Glarus folds and thrusts upon (A) Escher's conception of the double fold, and (B) Bertrand's view of overfolding and overthrusting (after Heim).

much impressed by the simplicity and the ingenuity of its conception; but after devoting the greater part of the season to examination of critical districts and to a study of sections across the central Alps, he became convinced of its insufficiency and of the general correctness of the now accepted Swiss view. There can be little doubt that this view is steadily gaining ground among those structural geologists who have given their attention to the subject.

Necessity for considering the mechanics of formation of arcuate mountains.—Though it be true that the theory of "overfolding and

[1] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithson. Misc. Coll.*, LVI, No. 31 (1912), 1–13.

overthrusting" as an explanation of Alpine structure is steadily gaining ground, it is none the less a fact that there is much criticism of the mechanics of the processes which have been invoked, and the writer believes that this criticism is well founded. Swiss geologists profess to regard this phase of the subject as of slight importance; but so long as it is necessary to reconstruct from incomplete surface indications folds which are in part concealed below the surface, the contention of these geologists can hardly be admitted to be justified. No better illustration could be offered than contrasting the "double fold" and the "blanketing nappes" theories as applied to the classical district of the Glarus (Fig. 1). Both theories involve complex structures which have never yet been found complete in any region, and discrimination between them must of necessity depend in some measure upon the possibility of accounting for their formation as a result of conceivable stress-strain conditions during a profound deformation of the region. In order to throw light upon their origin, all that is known of the mechanics involved in the folding process should be brought to bear, with due consideration of the fact that the Alps furnish a perfect illustration of the Asiatic type of mountain arc.

THE FOLDING PROCESS STUDIED IN THE PLAN—ARCUATE STRUCTURE

Areal and morphological characteristics of Asiatic ranges.—Study of a modern map of Asia upon which the relief has been indicated brings out some quite remarkable facts of distribution of the mountain ranges (Fig. 2). These facts might be stated in somewhat categorical form as follows:

1. The ranges are arcs which present their convex sides to the oceanic areas.

2. The arcs taken together in part inclose a relatively rigid mass of ancient rocks which from earliest geological times has been a land area and has become known to geologists as the Angara coign or shield.

3. The inner arcs of the series are the older and simpler in form and have the largest radius of curvature.

4. The intermediate and outer groups of arcs of the imperfectly concentric series are of later date and consist of festoons, or spring from a number of cuspate areas. This arrangement is described as "linking" or "syntaxis."

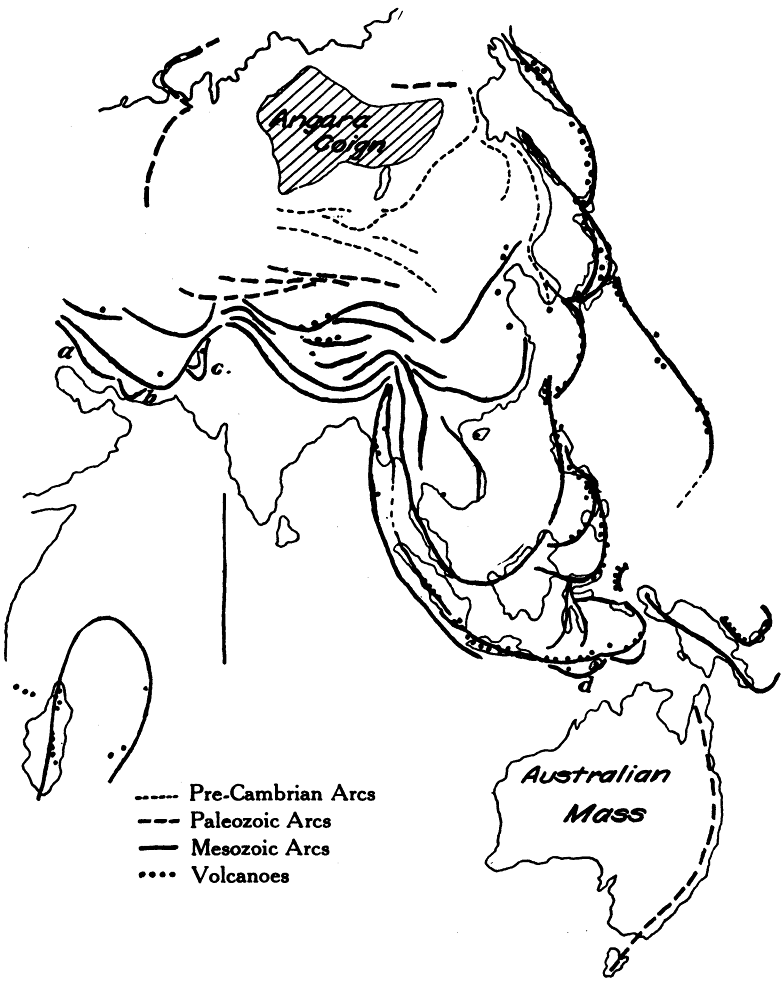


FIG. 2.—Sketch map of Asia to bring out the plan of the principal mountain ranges with indications of the partially submerged chains.

5. Several arcs of different radii in some cases spring from the same pair of linking areas which thus become centers of "virgation." The nearly parallel ranges near where they are linked are sometimes referred to as *coulisses* (Fig. 3).

6. Within the geologically recent peninsula which comprised the present Malayan peninsula, Indo-China and Malaysia, the arcs are developed in relatively much narrower and deeper festoons than elsewhere, thus giving the impression of having been subjected to strong lateral compression.

7. Locally and upon the outermost series of arcs, particularly, are superimposed arcs of smaller order of magnitude arranged after the manner of a scalloped border (Sewestan, Timor, etc., Fig. 2, *a*, *b*, *c*, *d*).

8. The outer group of arcs is paralleled by near-lying arcs of

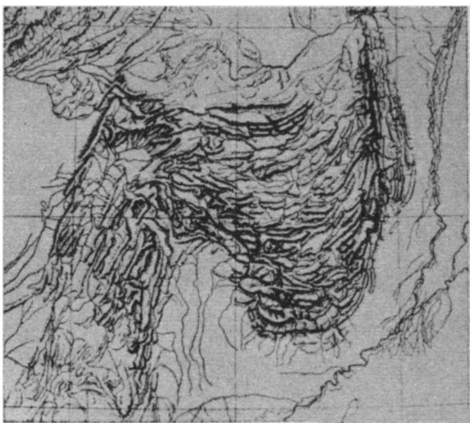


FIG. 3.—The multiple arc of Sewestan, British India (after de Saint Martin and Schrader).

volcanoes generally upon the concave margin, and these vents are characterized by unusually strong activity (see Figs. 2, 4, and 5).

9. Upon the convex margin of the outer series of arcs particularly lie "fore-deeps" (Fig. 5).

10. The outer series of arcs is characterized by extraordinary seismic activity (Fig. 6).

11. The outer arcs lying between the ancient Angara land-mass and the Pacific Ocean are to a marked degree asymmetric, each succeeding arc in the series springing from the side of its neighbor (see Fig. 2).

Structural peculiarities of the arcs.—Of all mountain arcs of strongly marked Asiatic type, the Alps have been most carefully

studied with respect to tectonic structure. Speaking broadly and in the usual terms, this arc consists largely of a series of sediments folded into closed recumbent flexures with axial planes which incline (except where the crown has sunk) toward the interior of the arc, and which are further extensively "overthrust" and "overridden"

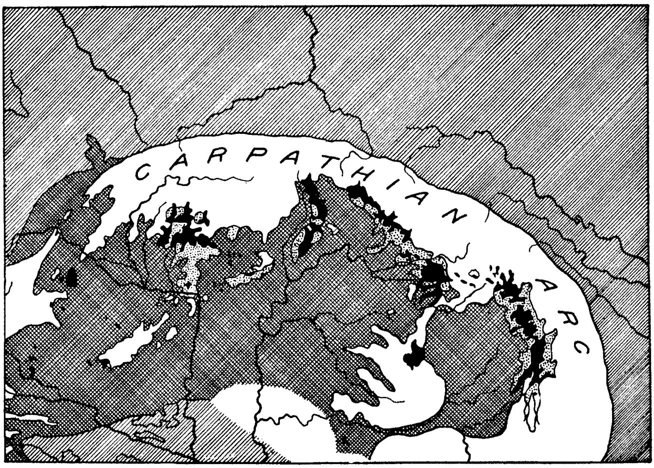


FIG. 4.—Arc of the Carpathians with volcanoes ranged upon the concave margin (after de Martonne).

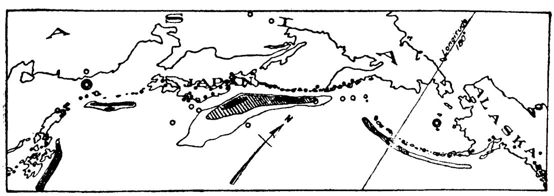


FIG. 5.—Sketch map to show the relation of fore-deeps and arcs of volcanoes to Asiatic arcs.

in the same sense. Such knowledge as we have of the arcs of Asia, now fortunately assembled and analyzed by Suess, indicates that in a very general way close recumbent folding and "overthrusting" is characteristic of them, and that the dip of the axial planes and the "thrusts" takes the same direction toward the interior of the arc. Quite recently a somewhat comprehensive tectonic study

of the Timor arc (*d*, Fig. 2) by Molengraaff[1] has shown a quite remarkable parallel with the *Deckenbau* of the Alps. Examples of "overthrusting" in extra-Asiatic arcs seem to be augmenting as these are studied with greater thoroughness.[2]

Centrifugal versus centripetal distribution of the active forces which produce mountain arcs.—In a broad way the great Asiatic mountain arcs no doubt owe their location to the presence of lenses of sediments laid down in former epicontinental seas along the borders of the growing continent of Angara. This fact alone would account for their essentially annular arrangement about the ancient coign of the continent as a center. It does not, however, explain the formation of the flexures or the places of location of the individual mountain arcs. There seems to be no difference of opinion that in some way the arcs are due to a system of tangential stresses which operated within the earth's outer shell. Suess has assumed that the system of stresses which produced the Asiatic arcs acted from *within the arcs outward*, or, in other words, was centrifugal, the more rigid and

FIG. 6.—Outline map of the Asiatic continent and neighboring archipelagoes to show (in black) the seismic zones. Note the close correspondence with the outer series of mountain arcs (Fig. 2) and with the zones of volcanoes (after de Montessus de Ballore).

[1] Paper read at the Twelfth International Geological Congress in Toronto, August, 1913.

[2] See A. Hamberg, "Die schwedische Hochgebirgsfrage und die Häufigkeit der Überschiebungen," *Geol. Rundsch.*, III (1912), 226–35; also Bailey Willis, "Überschiebungen in den Vereinigten Staaten von Nordamerika," *C.R. IX Cong. Géol. Intern.*, Wien, 1903 (1904), 531, 539–40.

hence resistant masses lying outside;[1] a view which has been rather generally accepted, it would seem, and which is followed, among others, by Arldt.[2]

To accepting this conception there is an insuperable objection from the standpoint of mechanics. The necessary reduction in area of the strata through duplication by folding and "overthrusting" is certainly great, and if this duplicated and often reduplicated expanse of strata has come from within the area inclosed by the arc, one of two consequences must have followed. Either a hiatus must have developed near the center of the area,

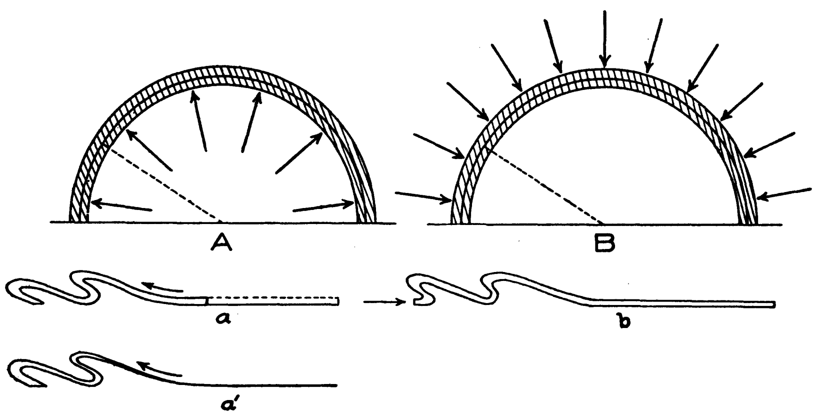


FIG. 7.—Diagrams to contrast the conceptions of centrifugally distributed (A) and centripetally arranged (B) forces in the production of mountain arcs. The lower figures are enlarged sections along the dotted lines, and the arrows in all cases give the directions of the (assumed) active forces.

or else the strata must have become greatly attenuated, an effect which should be increasingly apparent in the upper and later folds of the series and throughout in the upper limbs more than in the lower (Fig. 7, *Aaa'*). If, upon the other hand, the arcs are to be explained as a result of centripetally distributed forces coming from outside the area inclosed by the arc, these difficulties are not encountered for the reason that contraction of surface of large portions of the earth's outer shell may be assumed to supply the

[1] Ed. Suess, *Antlitz der Erde*, III, 1–2.

[2] Th. Arldt, *Die Entwicklung der Kontinente und ihrer Lebewelt*, Leipzig, 1907.

strata which are duplicated and reduplicated in the recumbent and "overthrust" folds (Fig. 7, *Bb*).

A centrifugal system of active forces implies that a mass relatively rigid and resistant with respect to that within surrounds the arc. Centripetally distributed thrusts, upon the other hand, imply that the area within the arc is relatively the more rigid and less capable of lateral migration.

Deductions concerning the relative age of Asiatic arcs.—If now we apply this criterion of distribution of thrusts, not to individual arcs alone, but to the Asiatic series as a whole, the centrifugal system of thrusts meets with a no less serious additional difficulty; for it would in this case be necessary to assume that the outer arcs were the first formed and the inner arcs the latest. Upon the other hand, a centripetal arrangement of active forces requires that the reverse should be true. That such is the case appears to be supported by at least four important considerations: namely, (1) the plan of distribution; (2) the position of the more rigid mass; (3) the known geological age of the ranges; and (4) the present locus of seismic and volcanic activity.

That the outer arcs of the system are, so to speak, laid on or applied to the inner ones is apparent from observation of the outline map (Fig. 2). More especially is this the case for the smaller arcs attached to the eastern wing of the great Burman Malaysian series and its extension to the north; as it is also for the arcs of Seyestan (Fig. 2, *c*) and Timor (Fig. 2, *g*).

As regards the position of the relatively more rigid area, we know that the Angara platform is an ancient land-mass which has been undisturbed since the Cambrian, whereas outside of the area of the arcs, if we except the remnant of the Gondwana continent in Hindustan and the separated mass of Australia, we encounter only the depressed oceanic basins.

The inner series of arcs, less clearly marked out morphologically as a result of long-continued erosion, we find to be of pre-Cambrian and Permo-Carboniferous age, though accompanied in some instances by later foldings. Farther out we encounter the great Tertiary welts of the Himalaya, Hindu-Kush, and their extensions which have been so recently elevated that erosive

processes have not yet succeeded in reducing their excessive relief. Still farther outward and upon the margins of the system, we have mountains which may more properly be described as in the making, with all the accompaniments of strong earthquake and violent volcanic eruption.

The ocean basins the loci of dispersion of tangential thrusts.—To this conclusion we are led by the considerations of the last section.[1] To the tectonic argument modern seismology has made a contribution of the first importance. Until within a quarter of a century it had been the custom to regard the continents as the regions of the most active geological movement upon our planet—a striking illustration of the assumed dominance of phenomena near at hand and often observed in fixing the basis of judgment. Yet a moment's thought shows us that the floors of the oceans are masked beneath a mobile cover which must effectively damp all disturbances that emanate from them. Now that a means has been discovered for seismically exploring this vast area and subjecting its movements to measurement, we have been surprised to learn that its mass movements are, area for area, vastly greater than those of that portion of the lithosphere which projects above the seas.

If we except the immediate vicinity of the continents, there is evidence that as a whole the movements upon the ocean floor are downward toward the earth's center, and hence the greatest reduction in superficies is there today in progress. Of this the evidence is twofold. By far the greatest of all macroseisms proceed from the deeper portions of the ocean floor, and we may draw the conclusion that if the mass movements were not in general downward rather than upward, these areas could hardly remain the deeps. On the other hand, except in the neighborhood of great deltas, most mountain shores of the continents are today rising. This is eminently true of that remarkable fringe of island arcs which lie to the eastward of the Asiatic continent, a fact amply demonstrated by the elevated shore lines and high coral reefs. The amounts of elevation are here further in direct proportion to

[1] See also T. C. Chamberlin and R. D. Salisbury, *Geology*, I, 517–18, 520–21.

the breadth of the fringes.[1] The narrow Liu Kiu and Kurile island arcs—mere lines of volcanic summits with no visible cordillera—show evidence of relatively slight elevation only, and these lie opposite the great sinking deltas of the Hoang and Yangtse in the one case and the Amur in the other. Still farther out toward the center of the Pacific, the Bonin group indicates some islands rising, others sinking, and still others rising after a depression—the group as a whole without as yet very strong indications of general uplift.

There is still the further argument that throughout the area of the coral seas, as was first pointed out by Charles Darwin and James D. Dana, working independently, the ocean floor has long been sinking, since in no other way can atolls be adequately accounted for.[2]

Any general movement of the ocean floors in the direction of the earth's center which is in excess of movement in the same direction in the continental areas must be accompanied by an out-thrusting against the continental margins such as would be required to explain the formation of mountain arcs uniformly facing the sea. That such thrusts are in reality carried out to the continents from the oceanic areas and cause landward migration of strata is also necessary to account for the fact that the elevation of mountains is not accompanied by tensional phenomena such as the gaping of fissures, etc. Mountain growth accompanied by strong earthquakes reveals in the behavior of rails, pipes, bridges, etc., the fact that not expansion but contraction of the surface has resulted from the movement.[3] The so-called block or *Schollen* theory of formation of mountains, amply demonstrated by observation in many regions, has had to contend with the supposed theoretical difficulty that opening of fissures by tension should result.[4]

[1] *Bull. Geol. Soc. Am.*, XVIII, (1907) 233–50, Pl. 5.

[2] The ingenious rival theories of Sir John Murray and other biologists fail utterly to explain certain necessary geological consequences. Professor Davis has utilized the Dana centennial to recall Dana's decisive discussion upon this point and to strengthen it by his own arguments.

[3] "A Study of the Damage to Bridges during Earthquakes," *Jour. Geol.*, XVI (1908), 636–53.

[4] *Proc. Am. Phil. Soc.*, XLVII (1909), 27–29.

So soon as we attempt to estimate the lateral migration of a point at the shore due to any given sinking of a definite arc upon the ocean floor, we find that the measure of the movement is probably insufficient to account for the duplication of strata in mountain folds. The landward migration corresponding to a uniform descent to a depth of one mile within an arc a thousand miles in width, if divided equally between the coasts on either hand, would amount to only about $1\frac{1}{2}$ miles, or, if concentrated upon one coast, to double that amount.[1] Account is to be taken, however, of a concomitant change in volume due to a relative elevation of isogeotherms into the descending sector of shell. Sedimentary rocks expand upon the average about $\frac{1}{190192}$ for each degree Fahrenheit, or 2.75 feet per mile per hundred degrees.[2] An arc of a thousand miles should thus be extended, from elevation of temperature in a uniform descent of one mile, a distance of between 1,985 and 2,770 feet, according to what figure is taken for the geothermic gradient. If this effect be added to that which is due to shortening of the arc, the expansion of the strata in the arc would be about $3\frac{1}{2}$ miles per thousand miles of arc. This figure, though somewhat small, is probably of the right order of magnitude to account for the duplicating of strata in mountain ranges.

If now we consider the possible effect of a disappearance through depression of the Gondwana continent upon outthrust toward the continent of Asia, we are warranted in assuming for Gondwana Land a fairly high level, for the reason that even within the tropics there was extensive glaciation. The average depth of the Indian Ocean may be taken as 4,200 meters, and the average descent of some three miles over an arc of 5,000 miles is not improbable. If this outthrust caused landward migration of strata upon the Asiatic shore only, the outthrust northward would correspond to a displacement of about 52 miles. This is, however, a maximum figure, and

[1] J. D. Dana estimated that within an arc corresponding to a quarter of the entire circumference of the globe, a uniform descent of 8 miles would cause a lateral displacement of 12 miles ("On the Origin of Continents," *Am. Jour. Sci.* (2), III [1847], 97).

[2] T. Mellard Reade, *The Origin of Mountain Ranges*, London, 1886, pp. 109–12.

should be diminished by any folding upon the opposite end of the arc, by reduction in volume of the strata, by any closing-up of joint spaces, etc.

In this connection it should not be overlooked that when the stage of sliding has been reached in the process of folding, the surfaces of dislocation in nearly horizontal attitude so facilitate underriding of strata that this may follow contraction without the necessity of infall of the depressed areas.

Form of the arcs and their distribution an expression of the space relations of continental pedestal and ocean floor.—If we are to assume the ocean basins to be the great loci of dispersal of compressive tangential stresses within the earth's shell, as brought out in the last section, we should examine each one of the Asiatic series of arcs to note whether it correctly expresses what is known of the distribution of ocean and continent and of deepening or shallowing conditions in the former at the time of arc evolution. In pursuing this inquiry we note that the Permo-Carboniferous arcs to the southward of the Angara coign should have a general east-and-west trend in order to correspond to thrust from the Tethys Sea which at the time of their formation stretched in that direction over what is now southern Asia and separated Angara land from the great Gondwana continent to the south. To the eastward of the ancient coign the general trend of the arcs should not, however, differ greatly from that of the later arcs in the same vicinity or of the shore line of today.

The extension of the Angara continent southward over the Paleozoic Tethys, and the formation of the Indian Ocean by the breaking-up and partial sinking of the Gondwana continent previous to the folding of the early Tertiary period, is likewise in conformity with the greater accentuation of the curvature of the Tertiary welts across southern Asia. The growing peninsula which in Tertiary time connected the Malaysian archipelago to Asia was partially protected from southerly thrust by the mass of Australia, while being pinched between the eastern sea in the Indian Ocean and the vast Pacific. We may thus perhaps account for the elongation of the Burman-Malay arcs and their noteworthy lack of symmetry as well.

The great central remnant of Gondwana land which in Cretaceous time joined Madagascar to Hindustan, stretching across the central zone of the present Indian Ocean, persisted in large part through the early Tertiary and may account for the main subdivision of the Tertiary arcs to the north of Hindustan as well as the well-defined compressed arc which still exists in part submerged to the northward of Madagascar.[1]

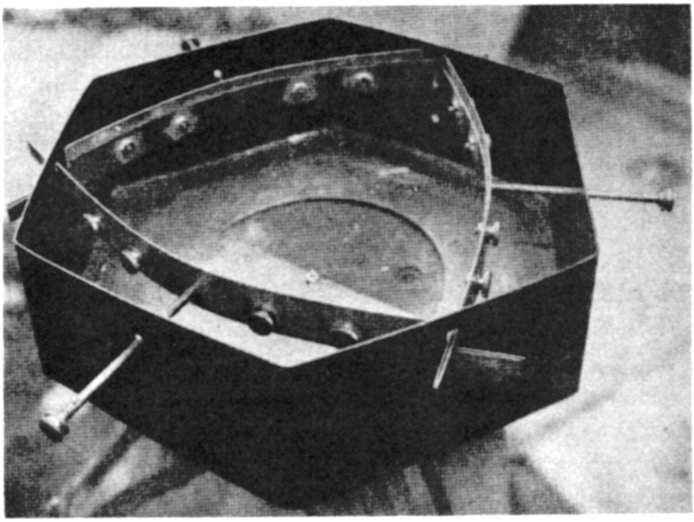
In later Tertiary time the Malaysian extension of the continent grew to the southeastward and the union of the two great seas to form the present Indian Ocean increased the thrust from the southwest and opposed more strongly that from the Pacific. From the south-southeastward the shielding mass of Australia should reduce the thrust upon the front of this arc and so favor its lateral compression from the oceans on either side. The smaller marginal arcs ranged in series, such as we find in the Philippine archipelago, show in macroseisms continued depression of their fore-deeps, and this indicates that the growth of the arcs may continue at a rapid rate after new arcs (here the Bonin) have begun to form farther out toward the central area of the ocean.

THE FOLDING PROCESS STUDIED IN THE PLAN—EXPERIMENTS WITH CONTRACTING FILMS

An imitation of arcuate structure may be produced by allowing slightly plastic films on stretched rubber sheets to contract after being locally rigified. This is best accomplished by use of hot Canada balsam spread in thin layer upon a sheet of stretched rubber such as is in use for the manufacture of bellows. An apparatus designed for such experiments is represented in Fig. 8 and consists of a strong metal frame within which three brass springs are so related to each other as to outline in the plan a plane equilateral triangle when in unstrained condition. When this triangle is manipulated by simple rods of metal notched upon the lower side, the degree of expansion of the triangle may be varied and maintained for any desired length of time. The springs which

[1] This arc is outlined upon Madagascar and in the Farquahar, Amirante, Seychelles, and Coetivy islands, the Saya de Malha Bank, and the Cargados, Mauritius, and the Réunion islands (see Fig. 2, p. 78).

A



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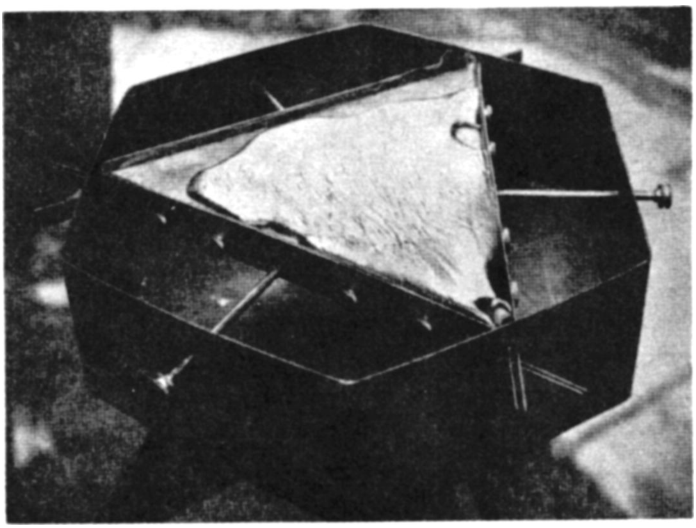

Fig. 8.—Apparatus for the simulation of mountain arcs through the contraction of locally rigified films of plastic material. *A*. View of frame with metal triangle in extended position. *B*. The same with sheet of rubber supporting a layer of Canada Balsam which was poured hot and when the rubber sheet was stretched, but was locally rigified and then forced to contract upon the relief of tension in the rubber.

compose the sides of the triangle are double and provided with clamp screws to permit of fastening the rubber sheet at its margins. When in use, the frame is placed upon a ring tripod, and since the frame is supplied with a window in its bottom, cold masses of metal of any desired shape may be introduced below and brought in contact with the under surface of the rubber sheet in order to induce local premature rigifaction of the cooling layer of balsam resting upon the sheet.

The principal difficulties encountered in carrying out the tests are due to the necessity of evaporating the balsam so that it will rapidly rigify in cooling and still be sufficiently fluid when poured upon the sheet to spread out into a thin layer. The evaporation can be accomplished upon a water bath, but a slightly higher temperature given it just before pouring is desirable. If the temperature is carried too high the surface of the rubber may be seriously affected.

The series of concentric arcs which appear in the balsam layer represented in Fig. 8 are due to the local rigifaction of a circular area near one side of the triangle but not centered upon a bisectrix, with the principal contraction of the sheet from the two sides opposite the convexity of the arc.